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Experimental Implementation of a Building Structure with a Tuned Liquid Column Damper Based on the Real-Time Hybrid Testing Method

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Abstract

In this study, the real-time hybrid test using a shaking table for the control performance evaluation of a U-shaped tuned liquid column damper (TLCD) controlling the response of earthquake-excited building structure is experiment-tally implemented. In the test, the building structure is used as a numerical part, on which a U-shaped TLCD adopted as an experimental part was installed to reduce its response. At first, the force that is acting between a TLCD and building structure is measured from the load cell attached on shaking table and is fed-back to the computer to control the motion of shaking table. Then, the shaking table is driven such a manner that the error between the interface acceleration computed from the numerical building structure under the excitations of earthquake and the fed-back interface force and that measured from the shaking table. The control efficiency of the TLCD used in this paper is experimentally confirmed by implementing this process of shaking table experiment on real-time.

Keywords: Taned liquid column damper; Real-time hybrid test

1. Introduction

Full scale tests on civil engineering structures such as buildings and bridges are very difficult or often practically impossible to be realized due to their size, weight, and cost etc. Therefore, their whole dynamic behaviors are generally evaluated based on the test results obtained by using a scale-down model or a non-linear part of the entire structure (Horiuchi et al., 2000 ; Iemura et al., 1999 ; Igarashi et al., 2000). In order to improve the performance of flexible structures that are sensitive to wind or earthquake loads, technologies of dissipating the structural energy by installing auxiliary mass have been developed and applied to building structures. Recently, the tuned liquid column damper (TLCD) has received the attention of researchers as a type of auxiliary mass system (Samali et al., 1998). TLCD has the control characteristics similar to that of tuned mass damper (TMD), which is one of most frequently used dampers for vibration control. Since the viscosity term in the governing equation of motion of TLCD is a function of the absolute value of liquid velocity, the equation is nonlinear and the dynamic characteristics of TLCD depend on the magnitude and the characteristics of excitation forces and the corresponding structural responses of the floor at which TLCD is installed (Yalla, 2001).

In this paper, the vibration control effect of a TLCD for a building structure excited by earthquake load is experimentally evaluated through the real-time hybrid shaking table testing method (RHSTTM). The RHSTTM doesn't require a physical building structural model in performing the experiment of a TLCD-

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structure interaction system and it only uses a TLCD as a test specimen. The structural responses of the interaction system are calculated numerically in real time by using the analytical structural model under the excitations of measured control force, user-defined base earthquake loads, and its state space realization is incorporated in the integrated controller of the shaking table. Also, in order to minimize the distortion of the acceleration of the shaking table, the inverse transfer function of the shaking table is identified and its state space realization is implemented in the shaking table controller. The shaking table reproduces the absolute acceleration of the TLCD installed floor by modulating the feedback gain of the shear force signal measured by the load-cell positioned between the TLCD and the shaking table. Comparison between the structural responses obtained by the RHSTTM and the conventional shaking table test of a single story steel frame with TLCD is made in order to verify the accuracy of the RHSTTM in both time and frequency domains.

2. Real-time hybrid testing method

Figure 1 shows the conceptual view of the experiment. The whole structural control system, which a TLCD was installed onto the structural model with n-degrees-of-freedom at its top story, is separated at their interface. As the result of that, the force interacts at their interface. The upper part of TLCD with the interacting force at its bottom is physically tested and the lower part of structural model with the interacting force and the input motion at its top story and base, respectively, is numerically calculated within the computer to control the motion of shaking table. For the experimental implementation, the interacting or control force generated by a TLCD, which is observed from a load-cell, is fed-back to the control computer. With the fed-back interacting force, the structural response of the story, where a TLCD is incorporated, is calculated from the numerical part. The shaking table excites the upper TLCD with this calculated response. These processes are carried out on real-time.

The numerical part with n-D.O.Fs, which is subjected to the excitations of the experimentally measured control force, $i_e(t)$, and the input acceleration, $\ddot{z}_0(t)$, at its top and bottom, respectively, as enclosed in dotted line in Fig. 1, is calculated by

$$\mathbf{M\ddot{Y}} + \mathbf{C\dot{Y}} + \mathbf{KY} = \mathbf{p} \tag{1}$$

where, $\mathbf{Y}$ is the absolute displacement vector, and the location vector of external forces with the length of n, $\mathbf{p}$ equals to $\{-i_e, 0, \cdots, 0, c_1\dot{z}_0 + k_1 z_0\}^T$. Also, the structural mass, damping and stiffness matrices are represented by

$$\mathbf{M} = \begin{bmatrix} m_n & & & \\ & m_{n-1} & & \\ & & \ddots & \\ & & & m_1 \end{bmatrix},$$
$$\mathbf{C} = \begin{bmatrix} c_n & -c_n & & \\ -c_n & c_n + c_{n-1} & -c_{n-1} & \\ \ddots & \ddots & \ddots & \\ & & -c_2 & c_2 + c_1 \end{bmatrix},$$
$$\mathbf{K} = \begin{bmatrix} k_n & -k_n & & \\ -k_n & k_n + k_{n-1} & -k_{n-1} & \\ \ddots & \ddots & \ddots & \\ & & -k_2 & k_2 + k_1 \end{bmatrix} \tag{2}$$

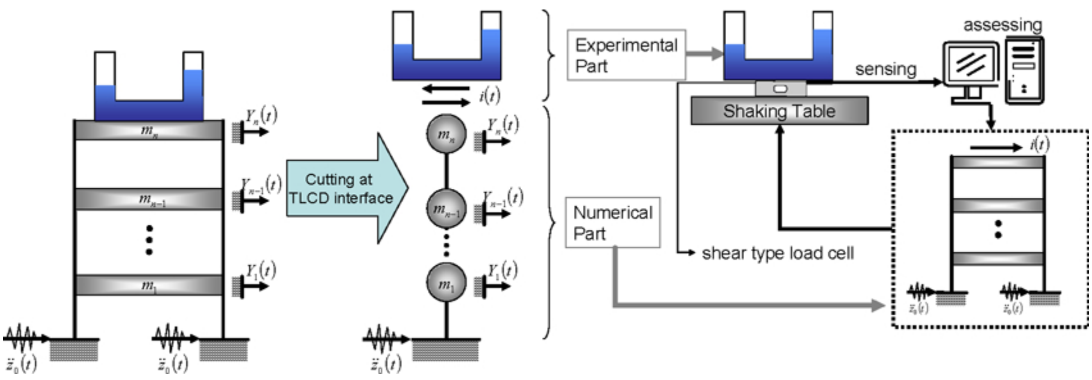


Fig. 1. Concept of the real-time hybrid testing method.

To calculate the numerical part such as Eq. (1) by a control computer on real-time, it is transformed into its state-space representation given by

$$\begin{aligned}\dot{\mathbf{z}} &= \mathbf{A}_c\mathbf{z} + \mathbf{B}_c\mathbf{u} \\ \mathbf{O} &= \mathbf{C}_c\mathbf{z} + \mathbf{D}_c\mathbf{u}\end{aligned} \tag{3}$$

where, the state variable vector, $\mathbf{z}$, with the length of $2n$ comprises the state variables, $\{\mathbf{y}_i,\ \dot{\mathbf{y}}_i\}^T$, in which the structural relative displacement, $\mathbf{y}_i$, equals to $\mathbf{Y} - z_o$. The input vector, $\mathbf{u}$, with the length of 2 consists of $\{-i_e,\ \ddot{z}_0\}^T$. The output vector, $\mathbf{O}$, with the length of n corresponds to the structural absolute acceleration, $\ddot{\mathbf{Y}}$, itself. The matrices $\mathbf{A}_c$, $\mathbf{B}_c$, $\mathbf{C}_c$ and $\mathbf{D}_c$ with the sizes of $2n \times 2n$, $2n \times 2$, $n \times 2n$ and $n \times 2$, respectively, are expressed as the following Eqs. (4)~(5).

$$\mathbf{A}_c = \begin{bmatrix} \mathbf{0}_{n\times b} & \mathbf{I}_{n\times n} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix},\ \mathbf{B}_c = \begin{bmatrix} \mathbf{0}_{n\times 1} & \mathbf{0}_{n\times 1} \\ \mathbf{M}^{-1}\mathbf{b} & -\mathbf{1} \end{bmatrix} \tag{4}$$

$$\mathbf{C}_c = \begin{bmatrix} -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix},\quad \mathbf{D}_c = \begin{bmatrix} \mathbf{M}^{-1}\mathbf{b} & \mathbf{0}_{n\times 1} \end{bmatrix} \tag{5}$$

where, $\mathbf{0}$ and $\mathbf{I}$ are the zero and unit matrices, respectively, with the size of $n \times n$. $\mathbf{0}$ and $-\mathbf{1}$ are the vector whose components are 0 and -1, respectively, with the length of $n \times 1$. $\mathbf{b}$ equals to $\{1,\ 0,\ \cdots,\ 0\}^T$ with the length of $n \times 1$.

3. Experimental system

In order to experimentally verify the proposed testing method, an experimental system shown in Fig. 2 was set up in Seismic Retrofitting & Remodeling Research Center at the Dankook University, Seoul, Korea. The TLCD was uniaxially excited by the shaking table on which it was mounted. The shear-type load-cell was installed between the TLCD and the shaking table to measure the base shear force yielded by the horizontal motion of the TLCD during the test. Also, an accelerometer was attached on the shaking table to monitor its motion. The data acquisition and implementation of the digital controller were conducted using a real-time digital signal processor (DSP). The primary tasks of the data acquisition board are the analog-to-digital (A/D) conversion of the measured force and acceleration data, and the digital-to-analog (D/A) conversion of the reference signal computed by the control program LabVIEW. An 8-channel data acquisition system was adopted using a NI PCI-6052E board and a NI SC-2345 B&C cable connector.

The motion of shaking table shown in Fig. 2 is driven by the control signal that is sent from control computer through DA channel of DAQ board. Without any compensation of dynamic characteristic of shaking table, the reference signal is different from the measured acceleration of table in their amplitudes and phases as the result of contamination of the reference signal due to dynamics between them. The inverse transfer function of the shaking table, from the measured acceleration of table to the reference signal within control computer, was used to cancel out the dynamic characteristics of shaking table

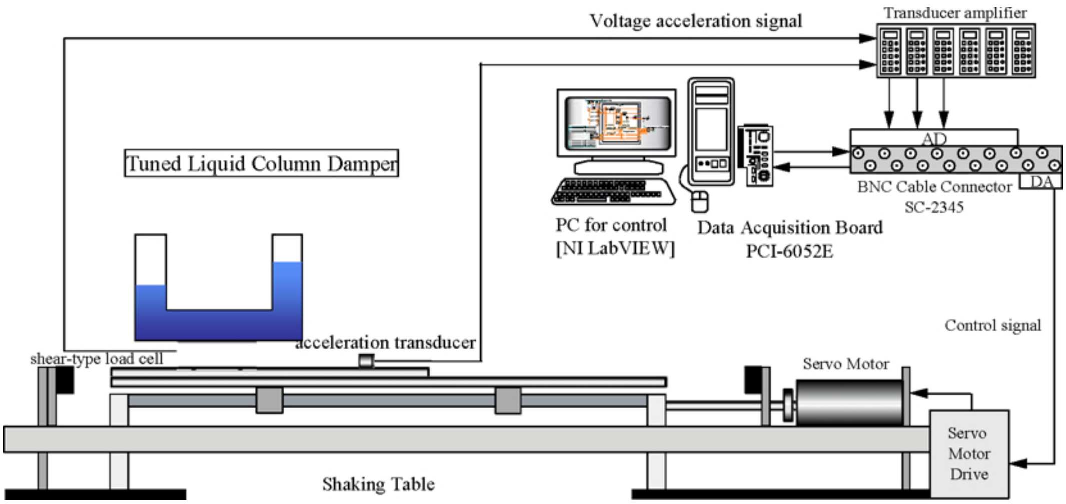


Fig. 2. Schematic illustration of real-time hybrid testing method using a shaking table.

system and to control its motion with one's intention. Based on this measured inverse transfer function of shaking table, it is approximated by the following 5-th order linear filter, and then the approximated one is reflected in the control computer as a shaking table controller.

$$G_n^{-1}(s)=\frac{0.6s^5+94s^4+10,746s^3+498,200s^2+167,124s+108,216}{s^5+204s^4+15,900s^3+8,252s^2+4,676s+405} \tag{6}$$

where, Laplace variable, s, equals to $i\omega$ with imaginary constant, i.

For its experimental implementation in the control computer, Eq. (6) is converted into the following state space realization.

$$\begin{aligned}\dot{\mathbf{x}}_s &= \mathbf{A}_s\mathbf{x}_s+\mathbf{B}_s r(t)\\ c(t) &= \mathbf{C}_s\mathbf{x}_s+D_s r(t)\end{aligned} \tag{7}$$

where $\mathbf{X}_s$, $r(t)$ and $c(t)$ are the state vector, the reference signal and the control signal of the shaking table controller, respectively. $\mathbf{A}_s$, $\mathbf{B}_s$, $\mathbf{C}_s$ and D_s are the system matrix with the size of 5×5, the reference signal influence matrix with the size of 5×1, the output matrix with the size of 1×5 and the coupling scalar coefficient between the reference and control signal, respectively.

4. Experimental verification

The numerical part and the shaking table controller discussed in previous sections should be integrated in the controller to implement the real-time hybrid test shown in Fig. 1. Figure 3 illustrates the block diagram for experimentally implementing the testing method. In the figure, the absolute acceleration is produced by the numerical part such as Eq. (3) with two inputs of the measured interacting force, $i_e(t)$, and not the measured but the prescribed earthquake record signal, $\ddot{z}_0(t)$, by a user within the control computer, as marked by the shaded area. The motion of shaking table is driven by the controller using the inverse transfer function to minimize the error between the controlled absolute acceleration, $\ddot{Y}_n(t)$, calculated as the top story response of structure and the actual shaking table acceleration, $\ddot{Y}_e(t)$. Accordingly, the shaking table itself behaves as the top story of structure, at which a TLCD is installed, and excites the upper TLCD that should be physically tested.

To verify the real-time hybrid shaking table testing method, firstly the conventional TLCD-structure interaction model shown in Fig. 4(a) is experimenttally implemented. Then, the hybrid test shown in Fig. 4(b), which the structural model in Fig. 4(a) is incorporated in the numerical calculation with its identified damping and stiffness coefficients and measured mass, is performed for the controlled case. Finally, two results from controlled cases are compared for the experimental verification of the real-time hybrid test.

The only shear-type structural model without the upper TLCD shown in Fig. 4(a) has the 0.6 m and 1.0 m of width and height and 169.7 kg of measured floor mass. Two records of El Centro and Kobe earthquake waves were excited by the shaking table

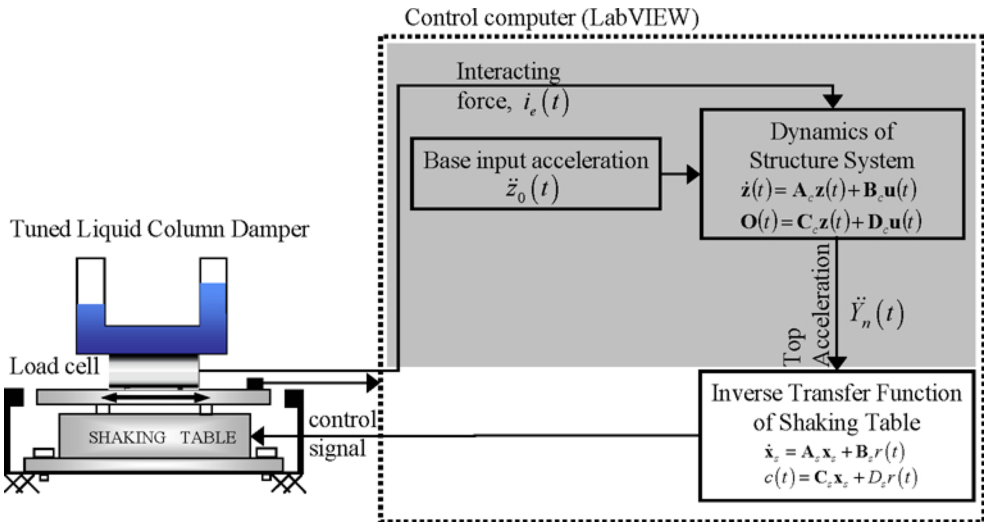


Fig. 3. Controller for implementing the real-time hybrid testing method.

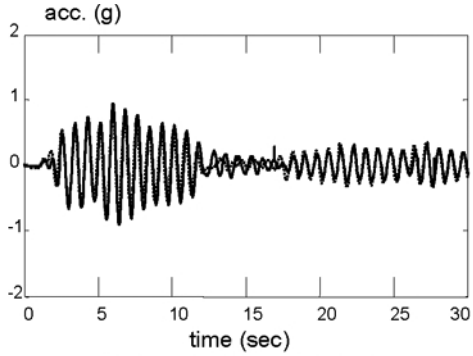
to measure the structural absolute acceleration. The identification was conducted with measured accelerations of the structure model and the shaking table. The identified parameters have slight differrences according to input earthquake waves. The averaged damping and stiffness coefficients were identified by $14.6\,N \cdot s/m$ and $9914.3\,N/m$, respectively, which correspond to 1.23 Hz of structural natural frequency. The level of water in a TLCD tank was adjusted to modulate the natural frequency of a TLCD to this identified structural one.

At first, the conventional shaking table test with this TLCD shown in Fig. 4(a) is performed to reduce the structural response. Two earthquake records with the maximum acceleration of 100 gal due to the shaking table performance are used to excite the TLCD-structure system with control case. Then, the hybrid shaking table test is conducted with the experimental set-up shown in Fig. 4(b). For its experimental implementation, the identified structural parameters are reflected in the numerical part

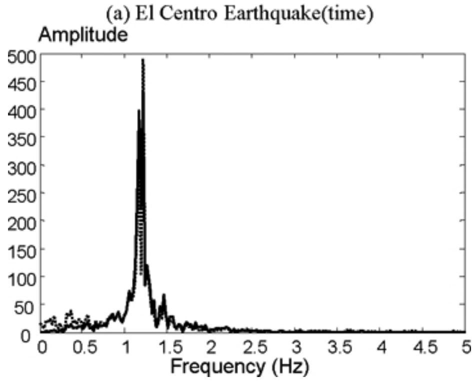
(a) Conventional testing method

(b) Real-time hybrid testing method

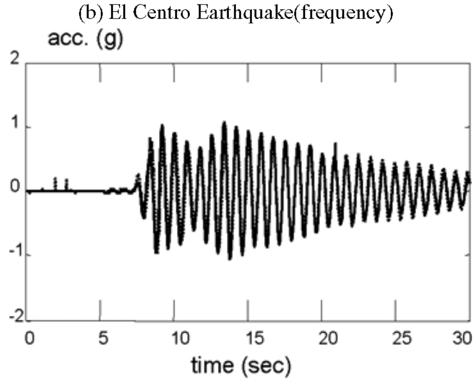
Fig. 4. Experimental view of a building with a TLCD.



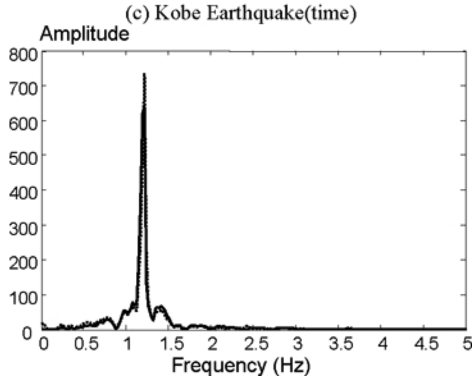
(a) El Centro Earthquake(time)



(b) El Centro Earthquake(frequency)



(c) Kobe Earthquake(time)



(d) Kobe Earthquake(frequency)

Fig. 5. Comparisons between the results from the conventional testing method(dotted line) and those from the RHSTTM(solid line) for the controlled response.

expressed by the shaded region in the integrated controller shown in Fig. 3. The continuous filters in the figure are converted into discrete ones with a time step of 0.01 sec in actual implementation of the experiment. Fig. 5 compare the controlled accelerations experimentally measured by implementing the conventional and the real-time hybrid shaking table tests in both time and frequency domains, respectively. The validity of the real-time hybrid shaking table test performed in this paper is verified from the fact that the experimental results from two methods well coincide with each other on the whole.

Conclusions

In this study, a real-time hybrid shaking table test was conducted to verify the seismic control performance of the TLCD installed in the building structures. The TLCD installed at the top floor of the structure is physically tested, and simultaneously numerical calculation is carried out for the assumed analytical structural model. Comparison between the structural responses obtained by the RHSTTM and the conventional shaking table test of a single story steel frame with TLCD indicates that the performance of the TLCD can be accurately evaluated using the RHSTTM without the physical structural model.

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